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# Ternary emergetic environmental performance auditing of a typical industrial park in Beijing

Guoxuan He [a], Jin Yang [a], Yi Lu [a], Saige Wang [a], Bin Chen [a, b, *], Tasawar Hayat [b, c], Ahmed Alsaedi [b], Bashir Ahmad [b]

[a] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China
[b] NAAM Group, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia
[c] Department of Mathematics, Quaid-i-Azam University, 45320, Islamabad, Pakistan

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ABSTRACT

An industrial park is characterized as a cluster of industries designed to meet compatible demands of different economic organizations within one location, which is pivotal to drive the regional economic growth of developing countries. The concentrated industrial activities inevitably result in substantial resource consumption and corresponding environmental emissions. Environmental auditing, which is used for the checking and verification of environmental performance, is an effective tool for investigating environmental emissions and resource consumption status and alleviation potential in industrial parks. As one of the environmental auditing technologies, emergy analysis, which provides a systematic approach in identifying the balance between socioeconomic development and natural environment, is employed in this paper. Specifically, a ternary emergetic environmental performance auditing framework was proposed to evaluate the behavior (preliminary work), ecological-economic efficiency (Level 1), environmental impact (Level 2), and mitigation effect (Level 3) of a typical industrial park in Beijing. The result showed that the concerned industrial park mainly depends on labor and service inputs and has a relatively high economic efficiency. However, the large dependence on purchased emergy exerted great pressure on the resource and environment, and affect the stability of the industrial park. The proposed framework may help reveal the value that free environmental services and resources offer to a specific system and thus can be complementary to the existing environmental performance auditing tools.



## 1. Introduction

Ecological limits cannot be exceeded in view of sustainability, which thereby posing unparalleled challenges on the regulation of human-nature nexus (Chen and Chen, 2007). In ecological-economic systems (such as cities, industrial parks), whether a production activity or engineering project is economically beneficial and environmentally friendly and how possibly the system is under sustainable and efficient development are key questions arousing increasing attentions (Chen and Chen, 2014). To answer these system-oriented questions, environmental auditing has been advocated by researchers during the last century.

Environmental auditing is considered as the way that organizations manage material and energy flows and regulate environmental performances so as to meet external demands (Mahwar and Verma, 1997; Sinclair-Desgagné and Gabel, 1997; Pagano and Immordino, 2007; Penini and Carmeli, 2010). It is formally defined as "a management tool comprising a systematic, documented, periodic and objective evaluation of how well environmental organization, management and equipment are performing with the aim of helping to safeguard the environment by: (i) facilitating management control of environmental practices; and (ii) assessing compliance with company policies, which would include meeting regulatory requirements" (Maltby, 1995), and has been widely used to define, verify and assess the environmental liabilities and legitimation, impacts of production and consumption activities, and health risk of wastes and pollutants. Since its first application to the US chemical and steel industries in 1970s, environmental auditing has played an increasingly significant role in

* Corresponding author. No 19, Xinjiekouwai Street, Beijing, 100875, China. Tel./fax: +86 10 58807368.
*E-mail address:* chenb@bnu.edu.cn (B. Chen).

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resource regulation and pollution control of production systems (Sinclair-Desgagné and Gabel, 1997). Some auditing standards and indicators were highlighted to provide quantifiable metrics of adopted strategies and environmental impacts (e.g., Nitkin and Brooks, 1998; Humphrey and Hadley, 2000; Beasley and Petroni, 2001; Balzarova and Castka, 2008). Diverse tools and methods were then introduced into the auditing framework (Humphrey et al., 2009). Nevertheless, the intrinsic interactions between auditing results and auditors' opinions and subsequent behaviors deserved further investigations in the field of environmental management (Tomlinson and Atkinson, 1987; McMillan and White, 1993). Therefore, environmental improvements by the public participation and behavior change were also incorporated into the auditing framework (Evans, 2003; Sahnoun and Zarai, 2009; Parmigiani et al., 2011). Subsequently, the environmental performance auditing, defined as the evaluation of an organization's responses (environmental strategies, objectives, targets, etc.) to the environmental impacts induced by its artificial activities, products or services (ISO, 2013), has been developed from the environmental auditing with particular emphasis on supervising the environmental performance legitimation, eco-economic efficiency, environ-strategies' effect and impact mitigation (Labuschagne et al., 2005), which provides more socioeconomic and environmental information of the productivity and utility of resource and natural capital to promote the integral benefits of the audited systems.

Evaluating the overall performance of industrial systems is of great significance for China, a polluted dragon facing high pressures on biocapacity (WWF, 2012), to meet its urgent requirement of sustainable transformation. However, in most cases of environmental performance auditing in China, finance status (e.g. the utilization of environmental fund, or other costs and benefits) of an enterprise is overemphasized, with few attention focused on environmental performance evaluation. Also, the absence of standardized evaluation systems, which are quite crucial to address key information of environmental impacts, precludes the description of the environmental behavior and ecological impacts (ISO, 2013; Perotto et al., 2008). To integrate environmental performance into auditing framework, emergy synthesis that gives consideration to both the natural properties and economic characteristics of a system provides a promising solution.

Emergy is defined as all available energy that is used, directly and indirectly, in making a product, expressed in units of one type of energy (Odum, 1996), which makes the comparison among different types of energy possible (Lu and Chen, 2014). Thus emergy synthesis is per se a supplier-side technique to reflect energy use of goods, fuel, labor and service in the generalized form of solar energy (Brown and Herendeen, 1996; Ulgiati et al., 2011). As a system-oriented approach, it has been proved to be a powerful tool in evaluating both environmental and economic costs in the progress towards sustainability (Campbell, 1997; Gasparatos et al., 2007; Gasparatos and El-Haram, 2009; Chen et al., 2010), and measuring the overall impacts on biocapacity at the interface between natural and anthropogenic systems (Chen and Chen, 2012). Within the framework of emergy accounting and evaluation, both direct and indirect information of a given system can be revealed by tracing the ecological-economic processes of production and consumption (Brown and Ulgiati, 1997).

As the focus of environmental performance auditing is “economic feasibility, efficiency, effectiveness”, emergy accounting, which is a feasible approach to evaluating the status and position of different energy carriers in the universal energy hierarchy, and gives consideration to both the natural properties and economic characteristics of a system, provides a fresh insight into the interpretation of audited systems' efficiency and sustainability. Based on emergy analysis, the proposed emergy based environmental performance auditing may achieve ecological-economic efficiency auditing, environmental impact auditing, and mitigation effect auditing. This paper aims to set up an environmental performance auditing framework based on emergy synthesis to investigate the system efficiency, environmental performance and mitigation effect of an industrial park. The remaining of this paper is organized as follows: Section 2 proposes an emergy synthesis based environmental performance auditing framework (tri-EmPA) based on the detailed introduction of emergy method. Section 3 illustrates a case study of a typical industrial park in Beijing and provides a systematic analysis on its comprehensive environmental performance using tri-EmPA. Finally, Section 4 draws the main findings and discusses the possible application of emergetic auditing framework in China.

## 2. Material and methods

### 2.1. Emergy synthesis

Based on thermodynamics and general systems theory, H.T. Odum pioneered the emergy theory in 1970s, and defined it as the available solar energy used up directly and indirectly to make a product or service (Odum, 1996). It can be considered as the “energy memory” or total solar energy embodied in matters, energies and services, and has been widely accepted as an effective energy accounting framework. Emergy synthesis is developed on the basis of the Maximum Empower Principle, which states that self-organized systems always tends to develop network connections to promote more useful work with inflowing emergy sources by reinforcing productive processes and overcoming limitations (Brown and Herendeen, 1996). Both natural and artificial systems (as audited objects) are guided by this fundamental principle to determine whether they will survive over time. It thus bridges up a linkage between human activities and natural supports, and reveal the possibility of system sustainability. In emergy synthesis, both ecological (e.g. raw materials) and economic (e.g. labor) inputs will be eventually converted in to solar emergy (sej) by multiplying them with each conversion factor. These factors indicate the solar emergy required to make 1 J of a given product or service, and has been defined as the solar transformity. The unit of transformity varies when the input items are expresses in different forms of units, for instance, the transformity units of mass and money are emergy/mass (sej/g) and emergy/money (sej/$), respectively. The emergy inputs can thereby by be calculated by multiplying the quantity of the input and its corresponding transformity.

When accounting emergy flows within a system, three categories of resource are identified generally, i.e., the emergy that could be obtained freely from the environment, including renewable resources such as sunlight, wind kinetic energy, earth cycle (R), non-renewable resources of soil loss (N), and the auxiliary purchased emergy, which includes fuels, materials, electricity, labor, etc. All these three categories are fundamental elements for emergy accounting and the understanding of the system interactions with the environment. The R and N flows are provided by natural environment and are economically free, whereas P is provided by human society and are usually accounted by fluxes associated with the economy, which can be regarded as recyclable and non-recyclable when they are utilized in the production, respectively. The sum of these inputs is the total emergy input (U), while the total products yield and service outputs from these inputs are the emergy yield (Y).

Emergy-based indicators offer suitable metrics to track the ecological and economic behaviors of a specific system, and evaluate the efficiency of emergy utilization, compare the effect of strategy improvement and overall impact of system operation.

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